MASTER

Dairy Farm Wind Energy Systems

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ABSTRACT

SUBSTITUTION of wind generated electric energy for utility power for typical dairy farm operations results in high system installed costs and a prorated price per kilowatt-hour for electricity that is unlikely to be attractive to the dairy farmer. A total energy conservant system, however, which combines conservation measures as well as a smaller wind machine results in savings of thousands of dollars in initial and annual expenditure. Eventually, wind energy costs may be obtained in the range of 3 to 5 cents/kWh for herd sizes between 200 and 500 in high wind regimes of 8 m/s, and 5 to 9 cents/kWh for herd sizes between 200 and 500 in medium wind regimes of 6 m/s, making the innovation more likely to be accepted.

INTRODUCTION

Considerable research effort has been devoted in recent years to the development and use of renewable energy resources in agricultural operations. One such potential air pollution-free energy resource is the wind. Buzenberg (1979) analyzed the wind energy potential applications in agriculture and found that if low wind system costs and high alternative energy costs ($0.08 per kWh) are assumed, wind energy substitution for utility power could be a viable economic venture in dairy farm operations in some states.

About 16 percent of the primary energy used in food production in the United States is consumed in the dairy sector (McGowan and Wendelgass, 1980). Dairy farm operations require a substantial and relatively constant level of energy. About 542 kWh (1,849,304 BTUs) per cow-year are used in dairy operations (Frank, 1975). Depending on geographical location, herd size and the degree of mechanization, 45 to 75 percent of this energy is used to cool milk and heat water to meet the sanitation standards. This energy is often in the form of expensive electrical energy.

McGowan and Wendelgass (1980) suggest that "load reduction, load management and energy recovery systems can combine with wind turbines to produce significant energy savings" in a dairy farm. Energy recovery systems which could be used in dairy milking operations include using tap water to precool the milk in a tube precooler (thereby preheating the water) or using the refrigeration compressor waste heat to heat water for sanitation purposes. The effect of the tube precooler and water heating condensing units is energy reduction in milking operations (Abarikwu and Meroney, 1982). For an alternate energy substitution system, this energy reduction leads to smaller sizes, smaller initial capital outlay, and thus produces a more favorable atmosphere for adoption of wind energy systems.

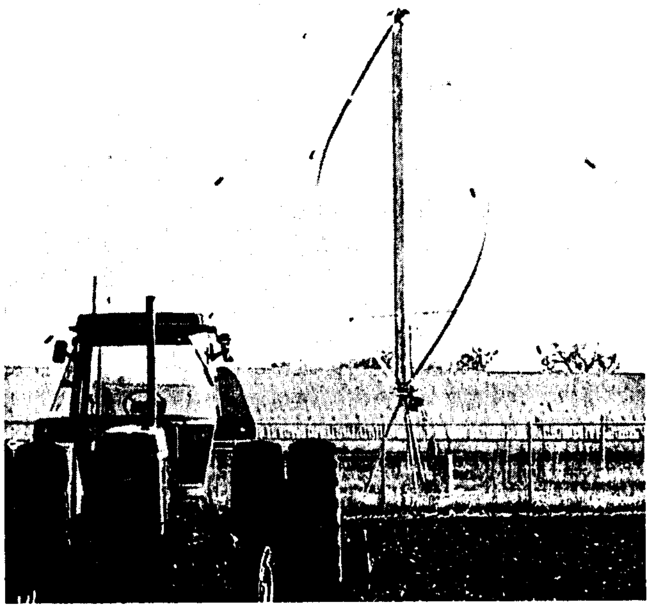

FIG. 1 Colorado State University 5 kW vertical axis wind turbine at the Diary Farm connected to precooler/heat pump energy system.

This paper presents a model for selection of a dairy wind energy system that substitutes wind generated electrical energy for utility electric energy to meet milk cooling and water heating energy requirements in dairy operations. The model physics are based on experiences developed with the Dairy Farm Wind Energy facility at Colorado State University shown in Fig. 1 (Abarikwu and Meroney, 1980). The sizes, installed costs, and annual wind energy cost of the diary wind energy system are determined for different herd sizes and mean wind speed regimes for herringbone parlor systems with and without energy recovery systems. The model predictions are then compared with production data for Small Wind Energy Conversion Sytsesm (SWECS) to validate the results.

DESCRIPTION OF DAIRY WIND ENERGY SYSTEM COMPONENTS

A schematic description of the dairy wind energy system components is given in Fig. 2. The utility grid provides a backup during extended lull wind periods in which system storage cannot meet energy demands and also acts as an extra storage for excess wind-generated electricity produced in zero demand periods. The wind turbine generates synchronous electricity to drive the heat pump producing ice for milk cooling and heat for water heating. It may be a horizontal or vertical axis wind generator.

Two energy recovery systems may be incorporated in

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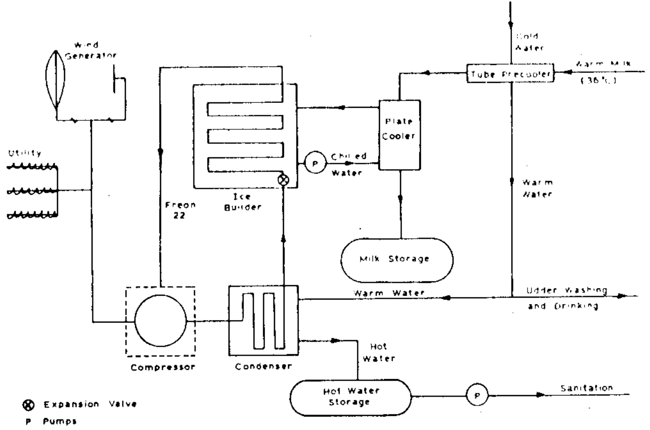

FIG. 2 Schematic drawing of dairy wind energy system components with energy recovery units—Level 1 energy conservation.

the system. The first, a tube precooler, precools the milk as heat is exchanged between tap water and warm milk. The warm water of this heat exchange process may be stored and used for udder washing and drinking in winter. The second energy recovery system is associated with the motor compressor (heat pump) which drives the refrigeration system. The evaporator provides chilling for an ice builder that supplies chilled water for use in the plate cooler. The ice builder makes ice that chills water for the plate cooler, and is sized to provide storage against lull periods of two days without the wind (Coty, 1976). The hot or condenser side may be modified to provide heat for heating sanitation water to a desired temperature. The hot water storage is insulated and also sized to provide storage capacity for lull periods.

The model discussed in subsequent sections evaluates circumstances which reduce system size, installed costs, unit cost and total annual cost of wind energy to acceptable limits, thereby making wind energy substitution attractive. A stand-alone wind system with a high energy use level requires bigger wind systems than wind systems combined with energy recovery systems. Four levels of design representing possible practical system configurations are considered, i.e., the wind system with both a precooler and condenser water heater, or with either of them or with none in a stand-alone situation. The performance parameters, i.e. size, installed cost, unit energy cost and annual energy cost, are evaluated for each configuration in an optimally sized herringbone parlor.

DAIRY FARM WIND GENERATOR MODEL

For the innovation of wind generated power to be acceptable to dairy farmers, it should be economically attractive. The Dairy Farm Wind Generator (DFWG) model compares the four dairy energy conservation levels for wind energy application possibilities. The optimal wind system parameters determined in each application for the same herd size and wind regime can be used as a guide to the most appropriate configuration that will encourage wind dairy applications.

The full program documentation and flowchart of the DFWG model are available in Abarikwu (1980). The required model inputs are the mean wind speeds at the desired hub height of the turbine, the rated powers of the turbine and the dairy herd sizes.

The model computes the milk cooling and water heating energy requirements at each level of energy conservation and selects the optimal herringbone parlor for each herd size using dairy milk production energy use functions developed by Abarikwu and Meroney, 1982.

For each mean annual wind speed, the wind speed distribution is computed using the Rayleigh distribution (Cliff, 1977) given by

$$f(V) = \frac{V\pi}{2\overline{V}^2} \exp - (V^2\pi/4\ \overline{V}^2) \qquad [1]$$

where

$f(V)$ = frequency distribution of wind speed
$\overline{V}$ = long-term mean wind speed
V = instantaneous wind speed.

The wind generator parameters are optimization variables in the DFWG model. The rated speed is the speed at which the wind generator attains its rated power. The capacity factor of a wind generator, however, decreases with an increase in the rated speed, (Justus, 1976). To caputre the maximum amount of energy from a given generator, the model selects the rated speed such that it is above the mean wind speed. This ensures that the energy content in the median wind speed is fully exploited at all times.

The cut-in speed is determined by the power required to turn the wind turbine at its synchronous rotational speed and to provide for generator, gearbox and aerodynamic losses (Coty and Vaughn, 1977) and is given after Buzerberg (1979) by

$$V_i = 0.4642\ V_r \qquad [2]$$

where

V_i = cut-in speed
V_r = rated speed.

The cut-out speed is defined by the maximum wind speed at which the wind turbine will produce usable power without damage to the system. It allows for the exploitation of wind energy over a wide spread of wind distribution spectrum, but implies higher rigidity. As indicated by Gunkel et al., 1979, the high capital costs involved in high cut-out speeds is not adequately compensated for in power output. The model determines the cut-out speed by minimixing generator downtime (after Cliff, 1977) using the equation

$$\overline{V}_{\text{min. downtime}} = \frac{\pi(V_o^2 - V_i^2)}{4(\ln V_o^2 - \ln V_i^2} \qquad [3]$$

where

$\overline{V}$ = mean annual wind speed at hub heights
V_o = cut-out speed.

One of the significant functions of the DFWG model is the determination of the wind generated electricity required to meet the milk cooling and water heating energy demands of a given herd from the computed turbine parameters. Generally the energy content of the wind is given by

$$P = \frac{1}{2} \rho\ A\ V^3 \qquad [4]$$

where

P = energy in the wind, dimensionally consistent
ρ = area swept by the wind generator
A = area swept by the wind generator
V = instantaneous wind speed.

The usable portion of the wind energy is determined by the aerodynamic efficiency of the blades, the electrical efficiency of the generators and the mechanical efficiency of the bearings. Because of the inefficiencies in the wind turbine which inhibit full extraction of the energy in the wind, the power produced by the wind turbine is given by

$$P_t = \frac{1}{2} C_p \rho A V^3 \quad [5]$$

where
C_p = power coefficient which is a function of the tip speed ratio, and
P_t = instantaneous wind energy extracted by the wind turbine.

In practice it is more convenient to estimate the energy produced from a wind turbine from its response function. The generator response function used by the model is:

$$P(V) = \begin{cases} 0 & ; 0 \leqq V < V_i \\ P_r(V/V_r)^3 & ; V_i \leqq V < V_r \\ P_r & ; V_r \leqq V < V_o \end{cases} \quad [6]$$

after Buzenberg (1979) where P(V) is the power output of the generator as a function of wind speed, and P_r is the rated power of the wind turbine. Combining equations [1] and [6], results in equation

$$\overline{P} = \int_{V_i}^{V_o} f(V) \cdot P(V)\, dv \quad [7]$$

where $\overline{P}$ is the average annual power output from a wind-powered generator in kWh.

Economic Assessment

The selection of the "best" wind generator for a particular application is based on the average cost per unit energy produced. The model computes the installed cost (land costs excluded) at 1979 dollars and the unit energy cost of the generated power. The cost function used by the model (after Buzenberg, 1979) is:

$$\ln(C) = 7.739 - 0.466 \ln(P_r) + 0.026 \ln(P_r)^2 \quad [8]$$

where C is the capital wind generator cost in dollars per kilowatt of rated power and $P_r \geqslant 1$ kW for wind generators rates at 11.18 m/s. The total capital cost, C_o, for the installed wind generator is determined by multiplying C by the rated power and Buzenberg's correction factor $(V_{ref}/V_r)^2$ where V_{ref} = 11.18 m/s.

The annual wind generator cost is computed on a uniform annual cost basis. The parameters for the computation which are in keeping with those recommended by Park and Schwind (1977) are listed in Table 1.

The values of installed cost and the annual wind energy cost depend on the cost function used in the model and the economic parameters assumed. However, the relative differences between the wind system costs will hold with different sets of reasonable assumptions.

TABLE 1. ECONOMIC PARAMETERS

Parameter	Value
Interest rate	15%
Investment credit	10%
Property tax rate	2%
Insurance plus operation and maintenance	2½%
Inflation rate on OP & M	10% per year
System life	20 years
Depreciation	Straight line
Salvage value	0

Using these parameters, a relation between unit energy cost, installed cost and average annual energy output is obtained.

$$C_e = 18.043\, C_o/\overline{P} \quad [9]$$

where
C_e = unit energy cost, ¢/kWh
C_o = installed cost of wind generator defined previously above, $, and
$\overline{P}$ = average annual energy output, kWh.

The unit energy cost is thus the base parameter for the selection of a wind system by the model once the energy demand has been met. Outputs of the model are the dairy energy demand, and the system parameters for the best wind system for the given configuration. These include the rated power, cut-in, cut-out and rated speeds, rotor diameter, annual system energy output, installed cost of the system and the unit energy cost.

RESULTS AND VALIDATON

The results from the model predictions are given for mean annual wind speed of 4.0 m/s and herd sizes of 50 to 500 in Figs. 3 and 4 for the four levels of energy management. The figures indicate that the annual and installed costs of wind generators in dairy application are extremely high without any energy saving devices. For full energy management, Level 1, the wind system costs about half as much as the stand alone wind generator system, Level 4, in a dairy farm application.

To partially validate the results of the model, a comparison is made with Rocky Flats actual SWECS prototype data for 1,000 units per year production*. The Rocky Flat prototype wind machines are all rated at 8.94 m/s and the comparison is made with model wind systems of same speed. Table 2 gives the comparative SWECS parameters between the Rocky Flats prototypes and the model predictions of optimal wind system design. There is a reasonable agreement between the model predicted design data and the prototype. Rocky Flats prototype machines have higher cut-out speeds than those recommended by the model and consequently have higher costs. The rotor diameter of the prototype machines are generally in agreement with the model predicted optimal system designs.

The very reasonable agreement between Rocky Flats prototype wind machines and the optimal wind system design of the Diary Farm Wind Generator model indicates that the model could be used as a guide in the selection of dairy farm wind systems. By relating rated power to the rated speeds, systems with costs lower than conventional manufactured prototypes are obtained by the model (see Table 2 columns (g) and (h)).

Figs. 3 and 4 show that wind energy application in dairy farm operations is much more attractive when energy saving management is combined with a wind generator. They also show that the precooler (level 2) is more effective than the condenser water heater (level 3), but using both (level 1) produces the best results. Many dairy farms have refrigeration systems that can be modified for condenser water heating at very minimal

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*Briggs, W. R. (1980). Personal communication, Systems Development, Wind System Program, Rockwell International, Golden, CO.

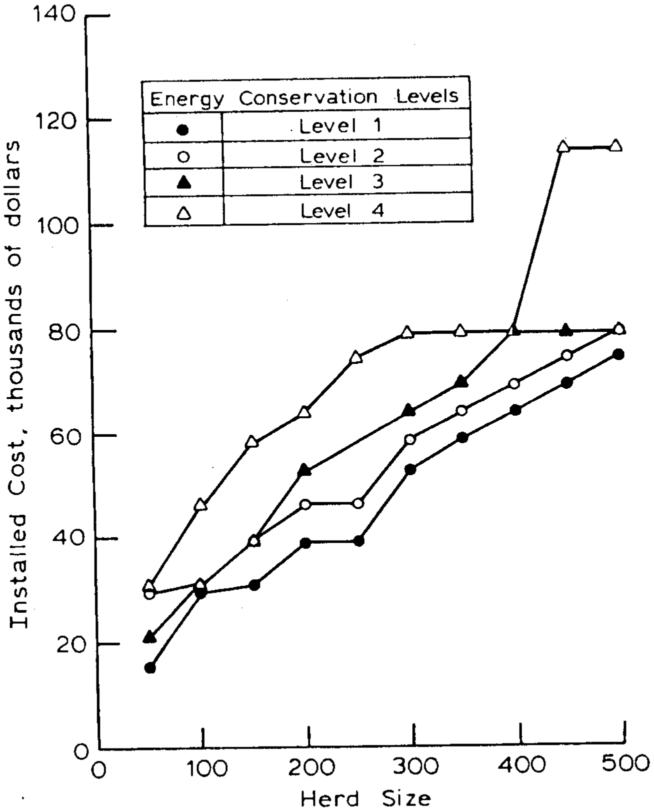

FIG. 3 Installed cost of optimal wind generators vs. lactating herd size at 4.0 m/s mean wind speed.

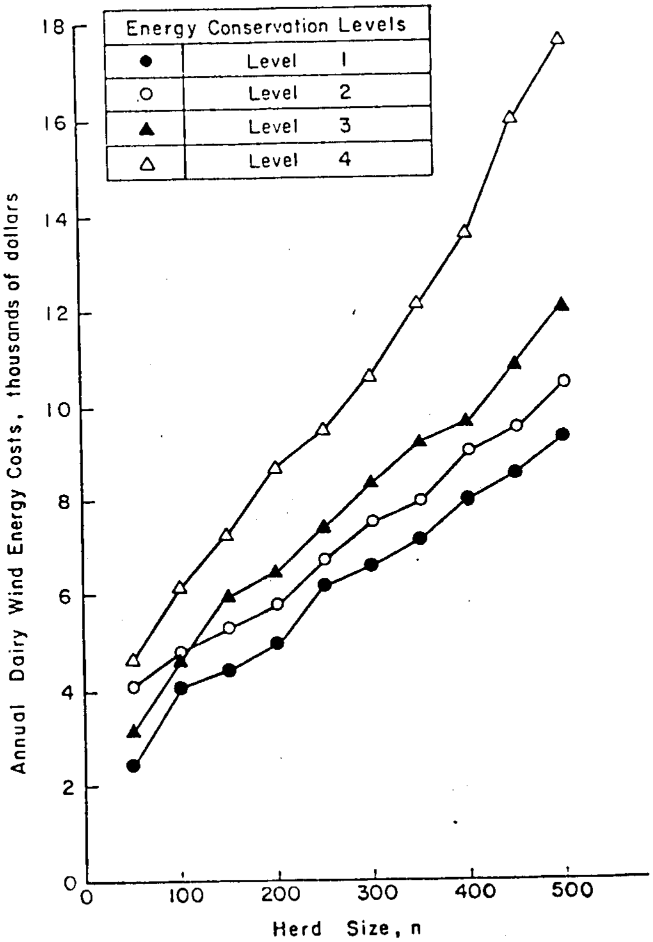

FIG. 4 Annual dairy wind energy costs vs. lactating herd size, for different energy conservation levels at 4.0 m/s mean wind speed regime.

costs. Tube precoolers can be fitted at less than $1,500 (1979 dollars). For systems incorporating these energy recovery units, wind energy substitutions may be a very economic and realistic proposition. Indeed it may be recommended that dairy farm wind systems be installed for only energy conservant system of such levels. Therefore, Figs. 5, 6 and 7 derived from the model for dairy wind systems with full energy management schemes have been included. Studies by McGowan and Wendelgass (1980) and Buzenburg (1979) indicate that there are dairy areas with mean annual wind speeds in the range of 4.0 to 8.0 m/s. For a herd size of 200, unit wind energy costs from 17 ¢/kWh at 4.0 m/s mean annual wind speed to 5 ¢/kWh at 8.0 m/s are possible, while for a herd size of 500, the corresponding costs are 11 ¢/kWh and 3 ¢/kWh (Fig. 6). From Figs. 5, 6 and 7 the following results are also deduced:

1 Installed cost, unit energy cost and the rotor diameter of a dairy wind generator decrease as the mean annual wind speed increases.

2 In a given wind regime, the installed cost and rotor diameter of a dairy wind generator increase with herd size, while the unit energy costs decrease.

CONCLUSIONS

The following conclusions could be drawn from the results:

TABLE 2. COMPARISON OF ACTUAL ROCKY FLAT SWECS PROTOTYPE DATA FOR 1,000 UNITS PER YEAR PRODUCTION (AFTER W. BRIGGS, 1980) WITH MODEL PREDICTIONS.

			Cut-in speed, m/s		Cut-out speed, m/s		Installed cost, $*		Rotor diameter, m	
Manufacturer	Power kW (a)	Rated speed† m/s (b)	Prototype (c)	Model (d)	Prototype (e)	Model (f)	Prototype (g)	Model (h)	Prototype (i)	Model (j)
Northwind	2	8.94	4.02	4.15	26.85	7.21—17.83	7787	5385	5.0	5.3
Enertech	2	8.94	3.58	4.15	25.04	7.21—17.83	7905	5385	5.0	5.3
Windworks	8	8.94	3.13	4.15	20.12	7.21—17.83	17879	12128	10.06	10.6
UTRC	8	8.94	3.58	4.15	15.65	7.21—17.83	18894	12128	9.45	10.6
Grumman	8	8.94	3.58	4.15	15.65	7.21—17.83	18937	12128	10.13	10.6
Kaman	40	8.94	4.47	4.15	26.82	7.21—17.83	31243	31129	19.51	23.7

*1979 dollars, assuming inflation rate of 12 percent per annum.
†All Rocky Flat prototype SWECS are rated at 8.94 m/s.

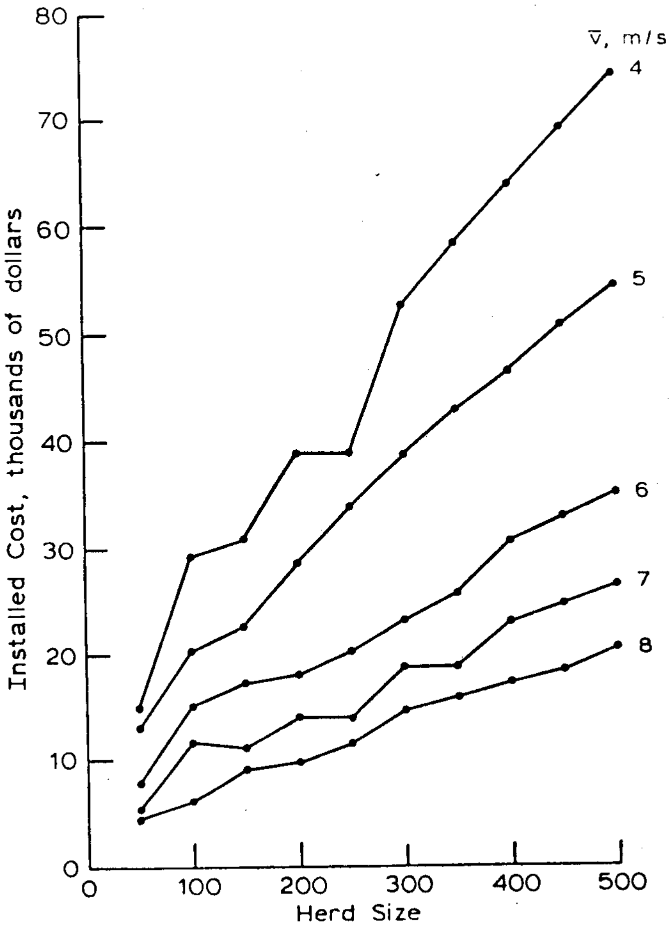

FIG. 5 Installed costs of optimal diary farm wind generators vs. herd size at different mean wind speed regimes for Level 1 systems.

1 The tube precooler is more effective than the condenser water heater in reducing dairy wind energy installed and annual costs. If both are combined in a dairy system, the installed and annual costs of dairy wind energy systems may be reduced by about fifty percent respectively.

2 By optimal design of wind system parameters and applying energy conservation measures, dairy wind systems with low unit energy and installed costs are possible and could be an attractive investment.

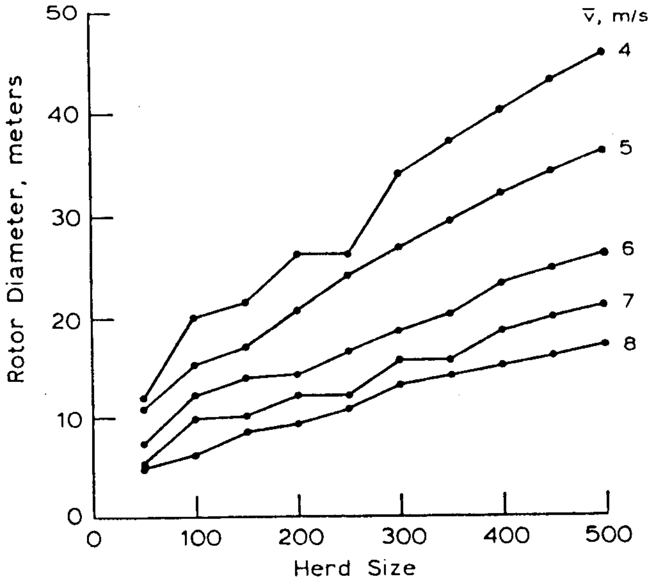

FIG. 7 Rotor diameters of optimal dairy farm wind generators vs. herd size at different mean speed regimes for Level 1 systems.

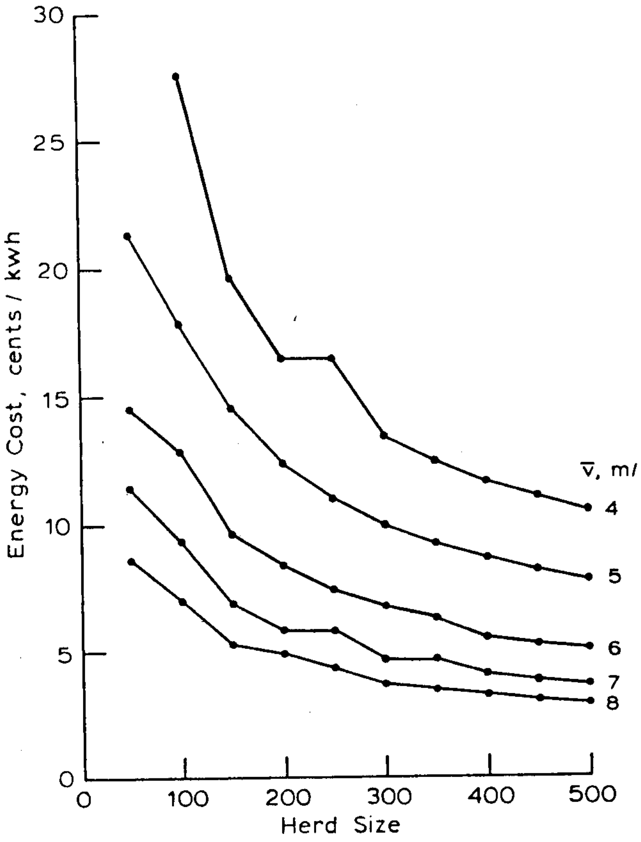

FIG. 6 Unit energy costs of optimal dairy farm wind generators vs. herd size at different mean wind speed regimes for Level 1 systems.

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